

Which baseline for neutrino factory could be better for discovering CP violation in neutrino oscillation for standard and non-standard interactions?

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Considering $\nu_e \rightarrow \nu_\mu$ and $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$ oscillations as the signals in neutrino factory we study the discovery reach of CP violation in presence of standard and non-standard interactions of neutrinos with matter. For standard interactions it is found that around 3000 Km baseline the discovery reach of CP violation is better for neutrino factory. Even this is better than the 130 Km baseline in superbeam facility but with the conservative choices of neutrino flux and detector specifications as given by GLoBES. However, the precision measurement of CP violating phase δ in neutrino factory is found to be good in the baselines ranging from 3000 Km to 4000 Km. In presence of non-standard interactions the discovery reach of CP violation for 3000 Km baseline is better than 130 Km superbeam facility in presence of non-standard interactions $\varepsilon_{e\mu}$ and also for most of the allowed region of $\varepsilon_{e\tau}$. However, 130 Km baseline is found to be better for $\varepsilon_{\mu\mu}$ and $\varepsilon_{\mu\tau}$. For other NSIs - ε_{ee} , $\varepsilon_{\tau\tau}$ the 3000 Km baseline in neutrino factory is better for smaller values of NSIs whereas 130 Km baseline with superbeam facility is better for larger values of NSIs. Compared to other baselines for neutrino factory the NSI discovery reach is in general better for 3000 Km baseline except for $\varepsilon_{\mu\tau}$ where as for example, 2300 Km baseline for superbeam is found to be better.

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I. INTRODUCTION

The present experiments on neutrino oscillations confirms that there is mixing between different flavours of neutrinos (ν_e, ν_μ, ν_τ). The probability of neutrino oscillations depends on various parameters of the neutrino mixing matrix-the PMNS matrix [1]. The current experiments tells us about two of the angles θ_{23} and θ_{12} [2] with some accuracy. The reactor neutrino experiments like Daya Bay[3] and Reno[4] provided compelling evidences for a relatively large angle θ_{13} , with 5.2σ and 4.9σ results respectively. These recent reactor neutrino results indicate θ_{13} very close to 8.8° . The CP violating phase δ is totally unknown. Although the mass squared difference of the different neutrinos ($\Delta m_{ij}^2 = m_i^2 - m_j^2$) are known to us but the sign of Δm_{31}^2 (which is related to mass hierarchy) is still unknown.

In this work we consider long baselines ($L > \mathcal{O}(2000)$ Km) for neutrinos coming from neutrino factory. However, it is difficult to consider short baseline below 2000 Km for neutrino factory as the first oscillation peak of oscillation probability will correspond to energy of order MeV for which proper neutrino flux will not be available. We consider totally active scintillator detector (TASD) for our study. Considering $\nu_e \rightarrow \nu_\mu$ and $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$ oscillations as the signals we do a comparative study of discovery reach of CP violation for different long baselines in neutrino factory as well as 130 Km baseline for superbeam in presence of standard and non-standard interactions. For the oscillation channel considered by us the detection of muon is required. However, this is supposed to be easier than the detection of electron which is required in superbeam. This is an advantage in considering $\nu_e \rightarrow \nu_\mu$ signal in the neutrino factory. There are some studies on the performance of low energy neutrino factories in the context of standard [5] and non-standard interactions [6] mainly for small θ_{13} . We have discussed the prospects of different baselines of neutrino factory considering large θ_{13} as obtained from Daya Bay experiment.

The paper is organized as follows: In section II we discuss $\nu_e \rightarrow \nu_\mu$ oscillation probability and how the δ dependent and independent part varies with the variation of matter density for baselines $L > \mathcal{O}(2000)$ Km for standard and non-standard interactions. In section III we discuss the experimental set-ups and the assumptions in doing the numerical simulations using GLOBES. In section IV for standard interactions we have shown the discovery reach of CP violation and the precision measurement of CP violating phase δ in different long baselines and also for 130 Km baseline in superbeam. In presence of non-standard interactions we show the discovery reach of CP violation depending on various NSI true values and also discuss the discovery reach of NSIs depending on δ true values. In section V we conclude with remarks on which baselines could be better for discovering CP violation after considering neutrino factory as well as superbeam for neutrino source.

II. $\nu_e \rightarrow \nu_\mu$ OSCILLATION PROBABILITIES WITH NSI

Apart from Standard Model (SM) Lagrangian density we consider the following non-standard fermion-neutrino interaction in matter defined by the Lagrangian:

$$\mathcal{L}_{NSI}^M = -2\sqrt{2}G_F \varepsilon_{\alpha\beta}^{fP} [\bar{f}\gamma_\mu P f] [\bar{\nu}_\beta \gamma^\mu L \nu_\alpha] \quad (1)$$

where $P \in (L, R)$, $L = \frac{(1-\gamma^5)}{2}$, $R = \frac{(1+\gamma^5)}{2}$, $f = e, u, d$ and $\varepsilon_{\alpha\beta}^{fP}$ are termed as non-standard interactions (NSIs) parameters signifying the deviation from SM interactions. Model dependent and independent bound

[7–9] are obtained for these NSI parameters. These NSI parameters can be reduced to the effective parameters and can be written as:

$$\varepsilon_{\alpha\beta} = \sum_{f,P} \varepsilon_{\alpha\beta}^{fP} \frac{n_f}{n_e} \quad (2)$$

where n_f is the fermion number density and n_e is the electron number density. As these NSIs modifies the interactions with matter from the Standard Model interactions the effective mass matrix for the neutrinos are changed and as such there will be change in the oscillation probability of different flavor of neutrinos. Although NSIs could be present at the source of neutrinos, during the propagation of neutrinos and also during detection of neutrinos [10] but as those effects are expected to be smaller at the source and detector due to their stringent constraints [9], we consider the NSI effect during the propagation of neutrinos only. In section IV in numerical simulations we shall consider the model independent allowed range of real values of different NSIs as mentioned in reference [9] for earth like matter.

In vacuum, flavor eigenstates ν_α may be related to mass eigenstates of neutrinos ν_i as

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i} |\nu_i\rangle; \quad i = 1, 2, 3, \quad (3)$$

where U is PMNS matrix [1] which depends on three mixing angles θ_{12} , θ_{23} and θ_{13} and one CP violating phase δ . The Hamiltonian due to standard (H_{SM}) and non-standard interactions (H_{NSI}) of neutrinos interacting with matter during propagation can be written in the flavor basis as:

$$H = H_{SM} + H_{NSI} \quad (4)$$

where

$$H_{SM} = \frac{\Delta m_{31}^2}{2E} \left[U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \alpha & 0 \\ 0 & 0 & 1 \end{pmatrix} U^\dagger + \begin{pmatrix} A & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \right], \quad (5)$$

$$H_{NSI} = A \begin{pmatrix} \varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon_{e\mu}^* & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon_{e\tau}^* & \varepsilon_{\mu\tau}^* & \varepsilon_{\tau\tau} \end{pmatrix} \quad (6)$$

In equations (5) and (6)

$$A = \frac{2E\sqrt{2}G_F n_e}{\Delta m_{31}^2}; \quad \alpha = \frac{\Delta m_{21}^2}{\Delta m_{31}^2}; \quad \Delta m_{ij}^2 = m_i^2 - m_j^2 \quad (7)$$

where m_i is the mass of the i -th neutrino and A is considered due to the interaction of neutrinos with matter in SM, G_F is the Fermi constant and n_e is the electron number density of matter. ε_{ee} , $\varepsilon_{e\mu}$, $\varepsilon_{e\tau}$, $\varepsilon_{\mu\mu}$, $\varepsilon_{\mu\tau}$ and $\varepsilon_{\tau\tau}$ are considered due to the non-standard interaction (NSIs) of neutrinos with matter. In equation (6), $(*)$ denotes complex conjugation. In our numerical analysis we have considered the NSIs - $\varepsilon_{e\mu}$, $\varepsilon_{e\tau}$ and $\varepsilon_{\mu\tau}$ to be real.

To discuss the variation of δ dependent and independent part in the oscillation probability and for that which baseline could be suitable for discovery reach of CP violation in presence of standard and non-standard

interactions we present below the oscillation probability $P_{\nu_e \rightarrow \nu_\mu}$ for long baseline ($L > \mathcal{O} 2000$ Km). To get these expressions of probability we have followed the perturbation method adopted in references [10–13]. We shall present the oscillation probability upto order α^2 considering small NSI of the order of α . Considering the the matter effect parameter A in the leading order of perturbation and NSI parameters $\varepsilon_{\alpha\beta}$ of the order of α one obtains

$$\begin{aligned}
P_{\nu_e \rightarrow \nu_\mu} = & \frac{\alpha^2 \cos^2[\theta_{23}] \sin^2 \left[\frac{AL\Delta m_{31}^2}{4E} \right] \sin[2\theta_{12}]^2}{A^2} \\
& + \frac{a_6 \sin^2[\theta_{13}] \sin^2[\theta_{23}]}{(-1+A)^3 E} \left(8E \sin^2 \left[\frac{(-1+A)L\Delta m_{31}^2}{4E} \right] - (-1+A)L\Delta m_{31}^2 \sin \left[\frac{(-1+A)L\Delta m_{31}^2}{2E} \right] \right) \\
& + \frac{a_1 \sin^2[\theta_{13}] \sin^2[\theta_{23}]}{(-1+A)^3 E} \left(-8E \sin^2 \left[\frac{(-1+A)L\Delta m_{31}^2}{4E} \right] + (-1+A)L\Delta m_{31}^2 \sin \left[\frac{(-1+A)L\Delta m_{31}^2}{2E} \right] \right) \\
& + \sin \left[\frac{(-1+A)L\Delta m_{31}^2}{4E} \right] \frac{\sin^2[\theta_{13}] \sin^2[\theta_{23}]}{(-1+A)^4 E} (2E(1+(-6+A)A \\
& + (1+A)^2 \cos[2\theta_{13}]) \sin \left[\frac{(-1+A)L\Delta m_{31}^2}{4E} \right] + 4(-1+A)AL\Delta m_{31}^2 \cos \left[\frac{(-1+A)L\Delta m_{31}^2}{4E} \right] \sin^2[\theta_{13}]) \\
& + \frac{4a_2}{(-1+A)A^2} \cos[\theta_{23}] \sin \left[\frac{AL\Delta m_{31}^2}{4E} \right] \left((-1+A) \cos[\theta_{23}] \sin \left[\frac{AL\Delta m_{31}^2}{4E} \right] (a_2 + \alpha \cos[\phi_{a_2}] \sin[2\theta_{12}]) \right. \\
& + 2A \cos \left[\delta - \frac{L\Delta m_{31}^2}{4E} + \phi_{a_2} \right] \sin \left[\frac{(-1+A)L\Delta m_{31}^2}{4E} \right] \sin[\theta_{13}] \sin[\theta_{23}]) \\
& + \frac{2\alpha \sin[\theta_{12}] \sin[\theta_{13}] \sin[\theta_{23}]}{(-1+A)^3 AE} \sin \left[\frac{(-1+A)L\Delta m_{31}^2}{4E} \right] \left(4(-1+A)^2 E \cos \left[\delta - \frac{L\Delta m_{31}^2}{4E} \right] \times \right. \\
& \cos[\theta_{12}] \cos[\theta_{23}] \sin \left[\frac{AL\Delta m_{31}^2}{4E} \right] + A \left((-1+A)L\Delta m_{31}^2 \cos \left[\frac{(-1+A)L\Delta m_{31}^2}{4E} \right] - 4AE \sin \left[\frac{(-1+A)L\Delta m_{31}^2}{4E} \right] \right) \\
& \times \sin[\theta_{12}] \sin[\theta_{13}] \sin[\theta_{23}]) \\
& + \frac{4a_2 a_3}{(-1+A)A} \cos \left[\frac{L\Delta m_{31}^2}{4E} - \phi_{a_2} + \phi_{a_3} \right] \sin \left[\frac{(-1+A)L\Delta m_{31}^2}{4E} \right] \sin \left[\frac{AL\Delta m_{31}^2}{4E} \right] \sin[2\theta_{23}] \\
& + \frac{4a_3}{(-1+A)^2 A} \sin \left[\frac{(-1+A)L\Delta m_{31}^2}{4E} \right] \sin[\theta_{23}] \left((-1+A)\alpha \cos[\theta_{23}] \cos \left[\frac{L\Delta m_{31}^2}{4E} + \phi_{a_3} \right] \sin \left[\frac{AL\Delta m_{31}^2}{4E} \right] \sin[2\theta_{12}] \right. \\
& + A \sin \left[\frac{(-1+A)L\Delta m_{31}^2}{4E} \right] \sin[\theta_{23}] (a_3 + 2 \cos[\delta + \phi_{a_3}] \sin[\theta_{13}]) \left. \right) \\
& + \frac{2a_5 \sin^2[\theta_{13}] \sin[2\theta_{23}]}{(-1+A)^2 A} \sin \left[\frac{(-1+A)L\Delta m_{31}^2}{4E} \right] \left(\sin \left[\frac{(-1+A)L\Delta m_{31}^2}{4E} \right] - \phi_{a_5} \right) \\
& + A \sin \left[\frac{(-1+A)L\Delta m_{31}^2}{4E} + \phi_{a_5} \right] - (-1+A) \sin \left[\frac{(1+A)L\Delta m_{31}^2}{4E} + \phi_{a_5} \right] \Big) \tag{8}
\end{aligned}$$

where

$$\begin{aligned}
a_1 &= A\varepsilon_{ee} \\
a_2 &= \frac{A\sqrt{|\varepsilon_{e\mu}|^2 + |\varepsilon_{e\tau}|^2 + (|\varepsilon_{e\mu}|^2 - |\varepsilon_{e\tau}|^2) \cos 2\theta_{23} - 2|\varepsilon_{e\mu}||\varepsilon_{e\tau}| \cos[\phi_{e\mu} - \phi_{e\tau}] \sin 2\theta_{23}}}{\sqrt{2}} \\
a_3 &= \frac{A\sqrt{|\varepsilon_{e\mu}|^2 + |\varepsilon_{e\tau}|^2 + (-|\varepsilon_{e\mu}|^2 + |\varepsilon_{e\tau}|^2) \cos 2\theta_{23} + 2|\varepsilon_{e\mu}||\varepsilon_{e\tau}| \cos[\phi_{e\mu} - \phi_{e\tau}] \sin 2\theta_{23}}}{\sqrt{2}} \\
a_5 &= A \left(|\varepsilon_{\mu\tau}|^2 \cos^2 2\theta_{23} \cos^2 \phi_{\mu\tau} + (|\varepsilon_{\mu\mu}| - |\varepsilon_{\tau\tau}|)^2 \cos^2 \theta_{23} \sin^2 \theta_{23} + \frac{1}{2} |\varepsilon_{\mu\tau}| ((|\varepsilon_{\mu\mu}| - |\varepsilon_{\tau\tau}|) \cos \phi_{\mu\tau} \sin 4\theta_{23} \right.
\end{aligned}$$

$$\begin{aligned}
& + 2|\varepsilon_{\mu\tau}|\sin^2\phi_{\mu\tau})^{1/2} \\
a_6 &= A(|\varepsilon_{\tau\tau}|\cos^2\theta_{23} + |\varepsilon_{\mu\mu}|\sin^2\theta_{23} + |\varepsilon_{\mu\tau}|\cos\phi_{\mu\tau}\sin 2\theta_{23}) \\
\phi_{a_2} &= \tan^{-1} \left[\frac{|\varepsilon_{e\mu}|\cos\theta_{23}\sin\phi_{e\mu} - |\varepsilon_{e\tau}|\sin\theta_{23}\sin\phi_{e\tau}}{|\varepsilon_{e\mu}|\cos\theta_{23}\cos\phi_{e\mu} - |\varepsilon_{e\tau}|\cos\phi_{e\tau}\sin\theta_{23}} \right] \\
\phi_{a_3} &= \tan^{-1} \left[\frac{|\varepsilon_{e\mu}|\sin\theta_{23}\sin\phi_{e\mu} + |\varepsilon_{e\tau}|\cos\theta_{23}\sin\phi_{e\tau}}{|\varepsilon_{e\tau}|\cos\theta_{23}\cos\phi_{e\tau} + |\varepsilon_{e\mu}|\cos\phi_{e\mu}\sin\theta_{23}} \right] \\
\phi_{a_5} &= \tan^{-1} \left[\frac{|\varepsilon_{\mu\tau}|\sin[\phi_{\mu\tau}]}{|\varepsilon_{\mu\tau}|\cos 2\theta_{23}\cos\phi_{\mu\tau} + (|\varepsilon_{\mu\mu}| - |\varepsilon_{\tau\tau}|)\cos\theta_{23}\sin\theta_{23}} \right]
\end{aligned} \tag{9}$$

For CP violation there is difference of probability in the neutrino oscillation and probability of antineutrino oscillation. One can relate the oscillation probabilities for antineutrinos to those probabilities given for neutrinos above by the following relation:

$$P_{\bar{\alpha}\bar{\beta}} = P_{\alpha\beta}(\delta_{CP} \rightarrow -\delta_{CP}, A \rightarrow -A). \tag{10}$$

In addition, we also have to replace $\varepsilon_{\alpha\beta}$ with their complex conjugates, in order to deduce the oscillation probability for the antineutrino, if one considers non-standard interaction during propagation.

To estimate the order of magnitude of δ dependent and δ independent part in the above two oscillation probability following Daya Bay result we shall consider $\sin\theta_{13} \sim \sqrt{\alpha}$. For only SM interactions, (i.e $\varepsilon_{\alpha\beta} \rightarrow 0$) in above expressions of oscillation probabilities one finds that the δ dependence occurs at order of $\alpha^{3/2}$. This order of dependence with δ remains same in the difference of neutrino oscillation probabilities and antineutrino oscillation probabilities (represented by ΔP later). However, the δ independent part in ΔP (which could mimic CP violation) is at order α . This happens due to matter effect through A for SM as can be seen from above expressions. Apart from this difference in the order dependence by $\alpha^{1/2}$, the parameter A plays a very crucial role in determining the variation of δ dependent (which varies as $1/A$) and δ independent part (which varies as $1/(1-A)$). We have ignored the variation of trigonometric functions (which depend on A) as the variation is much slower for A due to the baselines in the range of 2000 to 5000 Km. For relatively shorter baselines the A value is smaller and the δ dependent part becomes more pronounced. Apparently, it seems 2000 or 3000 Km baselines will be better than 4000 or 5000 Km baselines. However, it is important to note that for relatively shorter baselines the first oscillation peak will also correspond to relatively lower neutrino energy where the neutrino flux may not be that good. It is precisely for this reason that 2000 Km (as found in our numerical simulation) is not that good so far the discovery reach of CP violation is concerned.

However, when NSIs are also taken into account one can see that δ dependence in ΔP could occur at the order of $\alpha^{3/2}$ through a_2 and a_3 containing terms in (8) for NSIs of the order of α . We have checked that for slightly higher NSIs of the order of $\sqrt{\alpha}$ using perturbation method the same δ dependent terms in ΔP appears with a_2 and a_3 in the oscillation probability for long baseline as given in (8) and this slightly higher NSI makes these terms at the order of α which could compete with the δ independent part (which could mimic CP violation) in ΔP for long baseline as that is also at the order of α . So presence of slightly higher NSIs of order $\sqrt{\alpha}$ present in a_2 and a_3 improves the discovery reach of CP violation for longer baseline. As a_2 and a_3 contains NSIs like $\varepsilon_{e\mu}$ and $\varepsilon_{e\tau}$ it is expected that in presence of these NSIs the long baseline could provide a better discovery reach for CP violation.

III. NUMERICAL SIMULATION

In this work we have considered a neutrino factory set-up with four kinds of baselines which are : 2000, 3000, 4000 and 5000 km with 5.5, 7.1, 8.5 and 9 GeV parent muons respectively with 5×10^{21} number of stored muons and anti-muons decays per year. The energy of parent muons have been chosen in such a way that the energy corresponding to the peak of ν_e flux matches with the neutrino energy correspond to the first oscillation peak of the probability of oscillation $\nu_e \rightarrow \nu_\mu$ (fixing the probability for Standard Model interactions only) for different baselines. We have taken a magnetized totally active scintillator detector of mass 25 kt with threshold energy 1 GeV. In doing the analysis we consider a signal efficiency of 94% in appearance and 0.1% in disappearance channels. As signal we have taken the $\nu_e \rightarrow \nu_\mu$ oscillation and $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$ oscillations. As backgrounds we consider the neutral current events and ν_μ and $\bar{\nu}_\mu$ disappearance events. The systematic uncertainties of 2.5% and energy calibration error of 0.01% has been considered for both signal and for the background channels. The Gaussian energy resolution is considered to be $0.1\sqrt{E}$. The numerical simulation has been done by using GLoBES [14]. For the experimental setup of CERN to Frejus baseline of 130 Km and for 2300 Km for neutrinos and antineutrinos coming from superbeam we have considered the flux and detector specifications as considered in reference [15]. For discovery reach of CP violation we have compared with 130 Km baseline because there the discovery reach is found to be better in comparison to other baselines. For NSI discovery we have compared with 2300 Km baseline as the discovery limit is also found to be better in comparison to other baselines for superbeam.

We consider the true values of the neutrino oscillation parameters as $|\Delta m_{31}^2| = 2.45 \times 10^{-3} \text{ eV}^2$, $\Delta m_{21}^2 = 7.64 \times 10^{-5} \text{ eV}^2$, $\theta_{13} = 9^\circ$, $\theta_{12} = 34.2^\circ$ and $\theta_{23} = 45^\circ$. Also in calculating the priors we consider an error of 3% on θ_{12} , 0.005 on $\sin^2 2\theta_{13}$, 8% on θ_{23} , 4% on $|\Delta m_{31}^2|$ and 2.5% on Δm_{21}^2 . Also we consider an error of 2% on matter density .

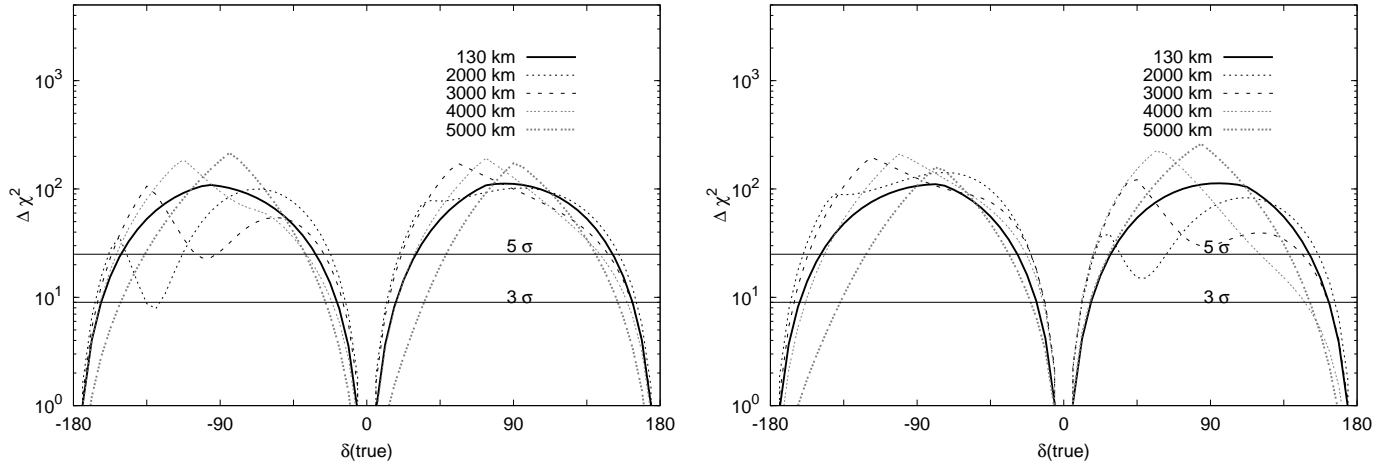


FIG. 1: Discovery reach of CP violation for only SM interactions for different baselines for normal (left panel) and inverted hierarchy (right panel).

In the figure 1 we have shown the CP violation discovery reach for 2000 Km, 3000 Km, 4000 Km and 5000 Km baselines for neutrino factory and 130 Km baseline for superbeam. It is found that 3000 Km baseline

for neutrino factory gives the better CP violation discovery reach than all other baselines considered for both the hierarchies of neutrino masses and for normal (inverted) hierarchy this discovery is possible over the 72 % (79%) of the allowed δ values. However, 130 Km baselines for superbeam seems better than other baselines for neutrino factory as shown above.

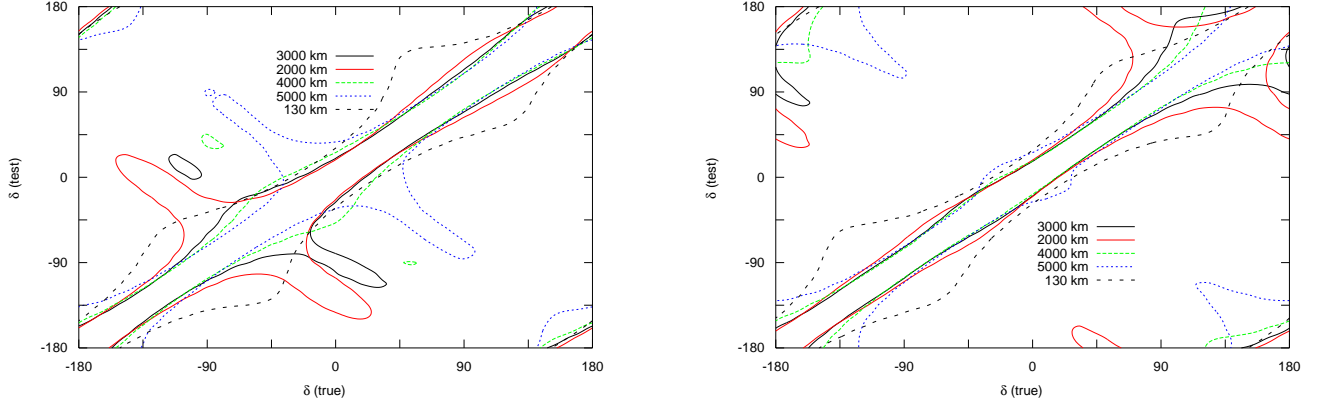


FIG. 2: Precision of measurement of phase δ for only SM interactions for different baselines for normal (left panel) and inverted hierarchy (right panel).

In figure 2 we have shown at 5σ confidence level the precision of measurement of phase δ for different baselines as considered for CP violation discovery reach. From the figures one may find out the precision ($P_{\delta(true)}$) of sensitivity of measurement for any true value of δ using the following expression for it:

$$P_{\delta(true)} = \frac{\delta(test)(max) - \delta(test)(min)}{2\pi + \delta(test)(max) + \delta(test)(min)} \quad (11)$$

where $\delta(test)(max)$ and $\delta(test)(min)$ are the maximum and minimum $\delta(test)$ values respectively corresponding to certain true values. Here also it is found that for most of the $\delta(true)$ values the precision of measurement is found to be better for 3000 Km baselines particularly for normal hierarchy in comparison to other baselines. As for example for $\delta(true) = 0$ the precision for normal(inverted) hierarchy is about 26 % (18%) and for $\delta(true) = \pi/4$ the precision for normal(inverted) hierarchy is about 9 % (14%). Although for inverted hierarchy 4000 Km baseline is slightly better.

In figure 3 we have shown at 5σ confidence level the discovery reach of CP violation in presence of NSIs ϵ_{ee} , $\epsilon_{e\mu}$ and $\epsilon_{e\tau}$ for baselines 3000 Km and 5000 Km baselines for neutrino factory and 130 Km baseline for superbeam.

In figure 4 we have shown at 5σ confidence level the discovery reach of CP violation in presence of NSIs $\epsilon_{\mu\mu}$, $\epsilon_{\mu\tau}$ and $\epsilon_{\tau\tau}$ for baselines 3000 Km and 5000 Km baselines for neutrino factory and 130 Km baseline for superbeam. In general, it is found that 3000 Km baseline in neutrino factory is somewhat better for smaller NSI values. However, for higher allowed NSI values 130 Km baseline for superbeam is found to be better in general. But for $\epsilon_{e\mu}$ and $\epsilon_{e\tau}$ the CP violation discovery reach is much better for almost all allowed NSI values. The possible reason for this significant improvement is discussed in section II in the context of the

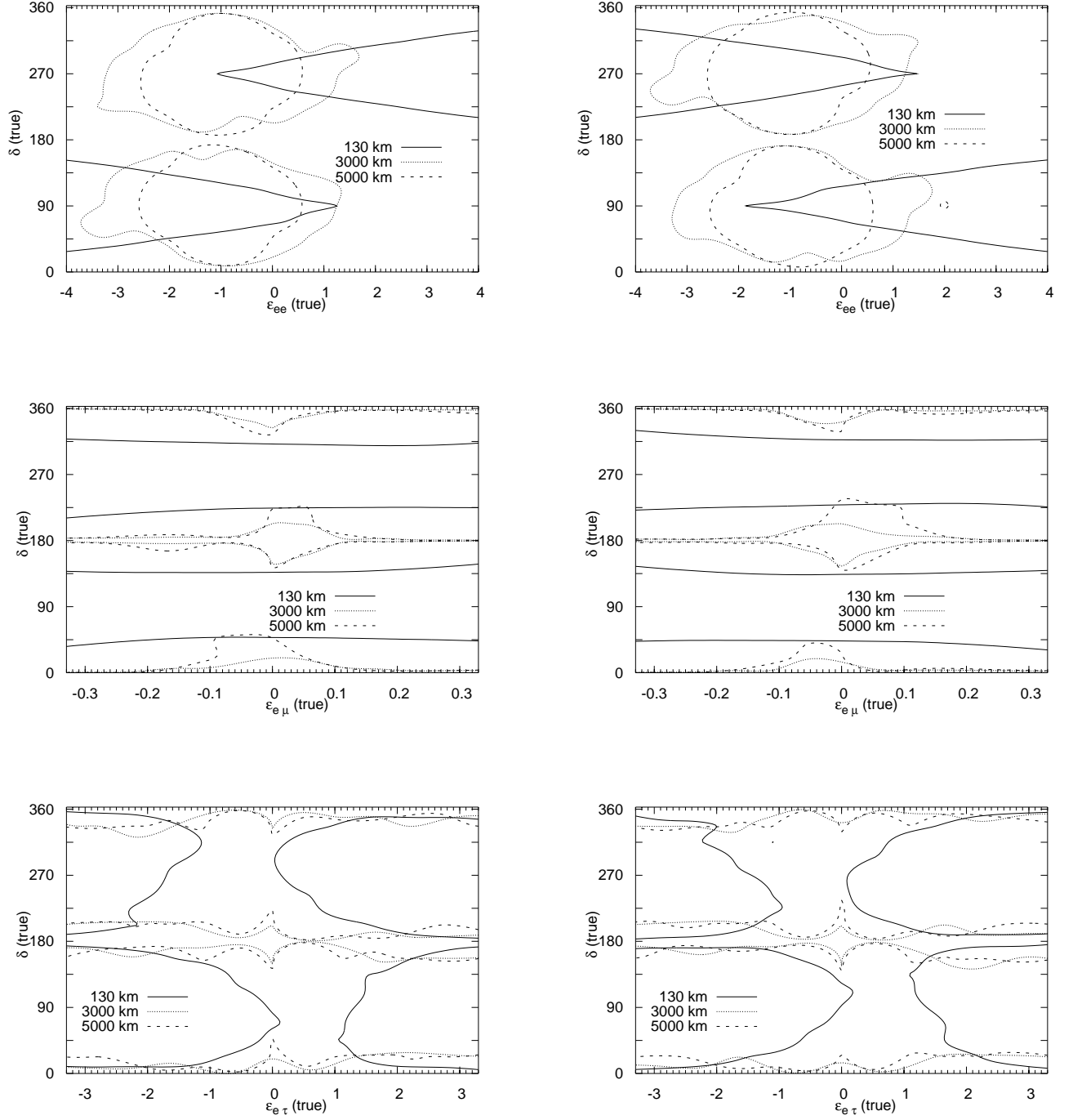


FIG. 3: Discovery limit of CP violation with NSI for both NH (left panel) and IH (right panel) at 5σ confidence levels for ϵ_{ee} , $\epsilon_{e\mu}$ and $\epsilon_{e\tau}$.

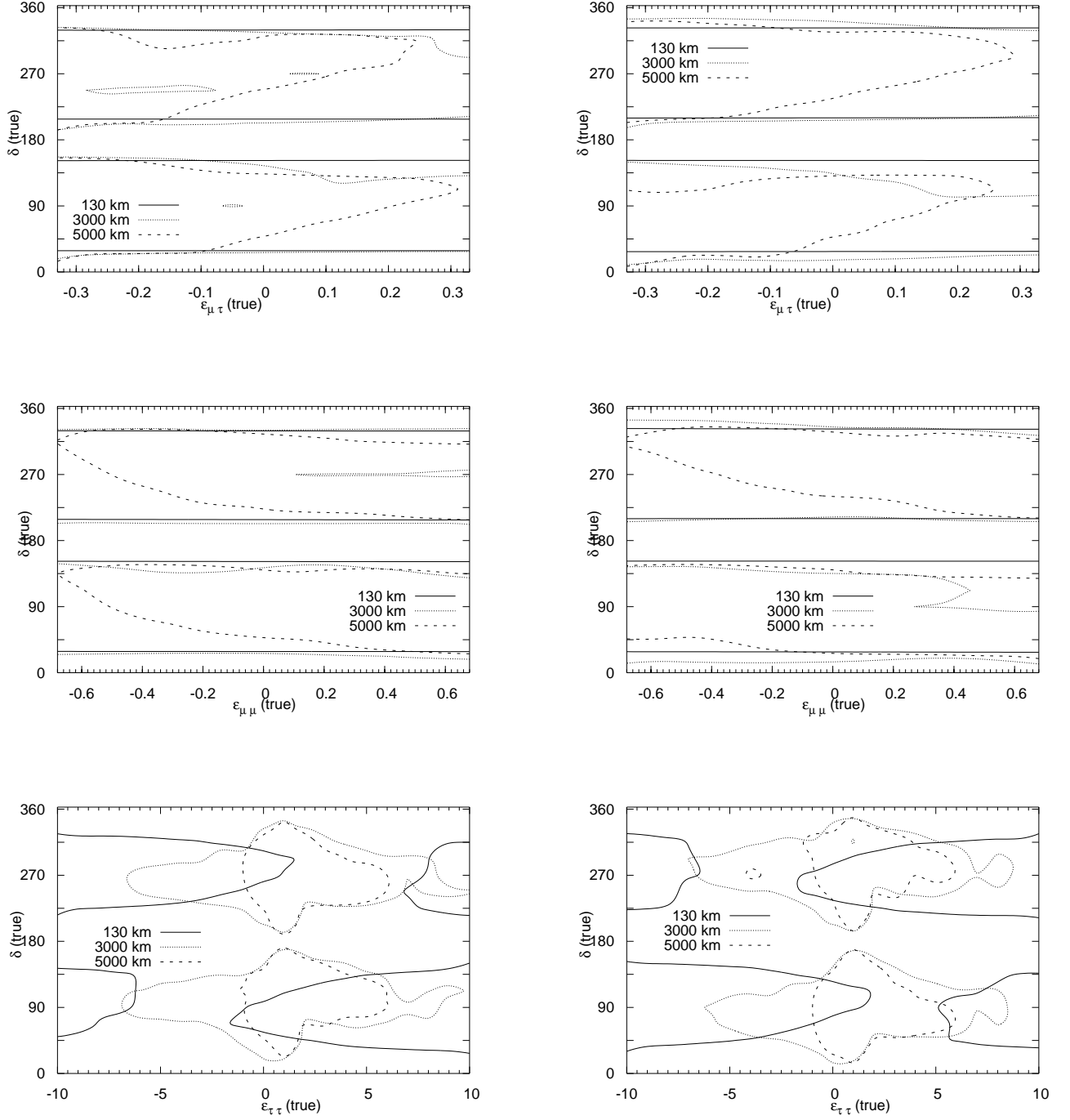


FIG. 4: Discovery limit of CP violation with NSI for both NH (left panel) and IH (right panel) at 5σ confidence levels for $\epsilon_{\mu\mu}$, $\epsilon_{\mu\tau}$ and $\epsilon_{\tau\tau}$.

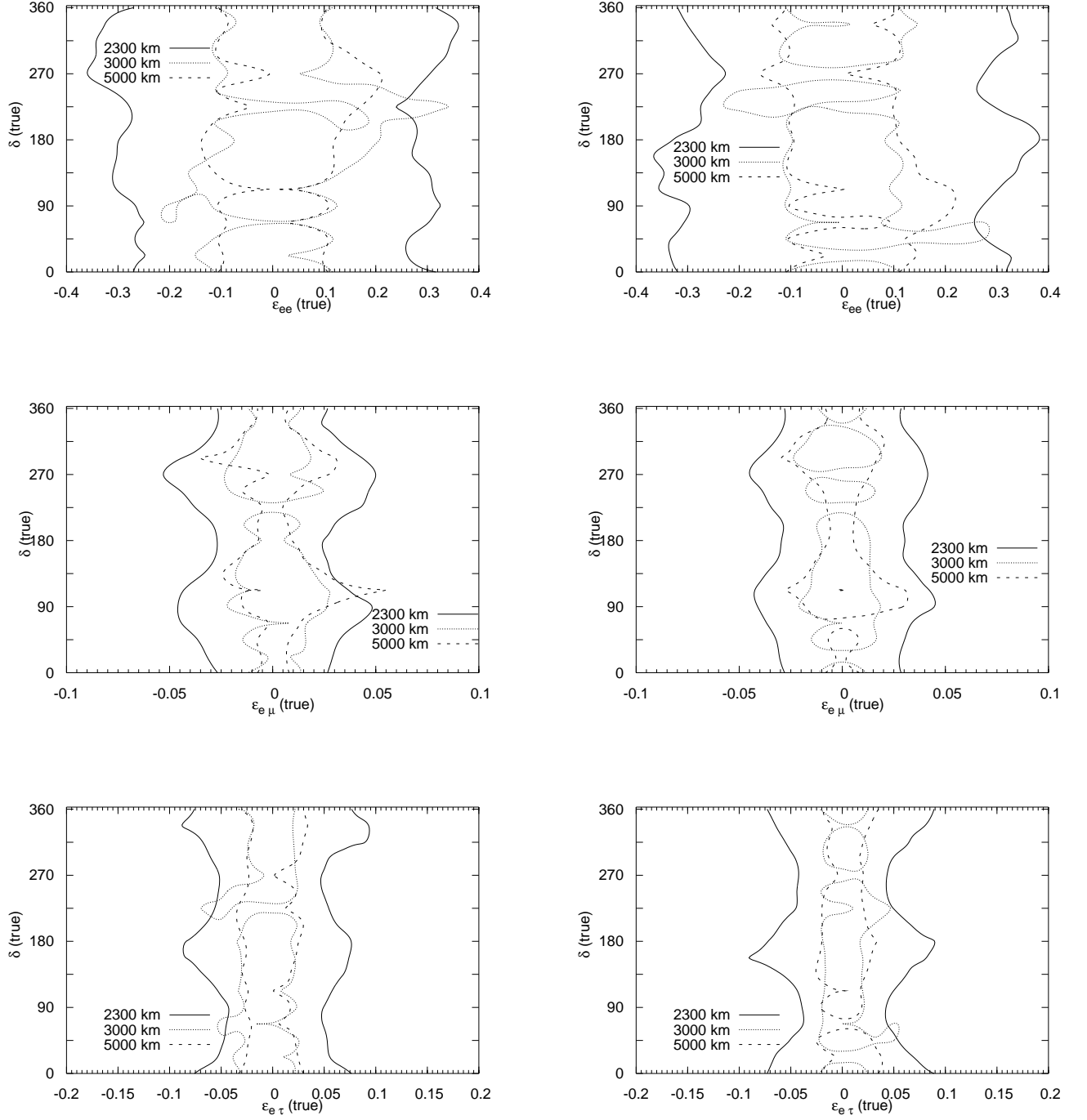


FIG. 5: Discovery limit of NSI for both NH (left panel) and IH (right panel) at 5σ confidence levels for ϵ_{ee} , $\epsilon_{e\mu}$ and $\epsilon_{e\tau}$.

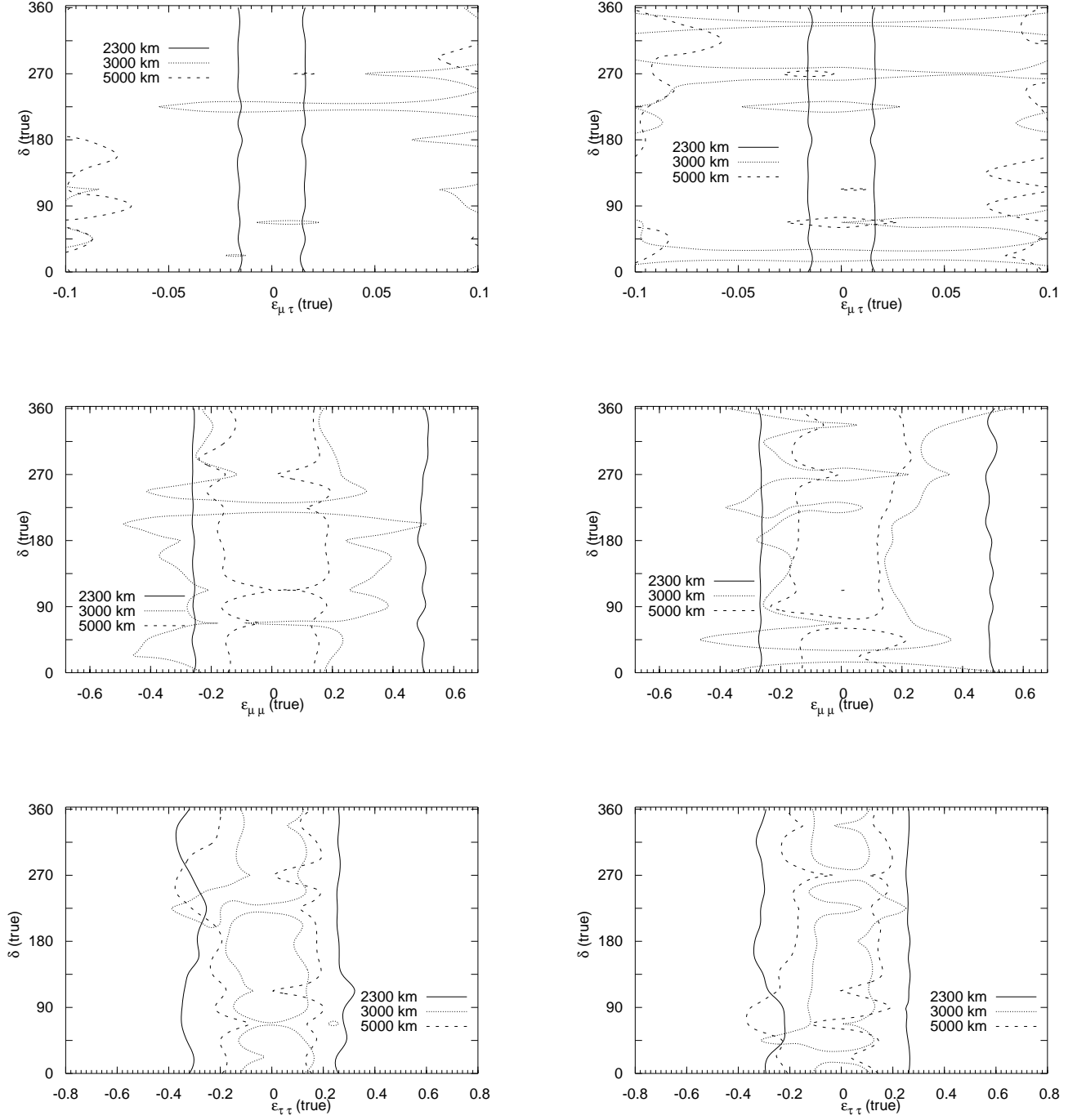


FIG. 6: Discovery limit of NSI for both NH (left panel) and IH (right panel) at 5σ confidence levels for $\epsilon_{\mu\mu}$, $\epsilon_{\mu\tau}$ and $\epsilon_{\tau\tau}$.

oscillation probability. For 3000 Km baseline for ϵ_{ee} , $\epsilon_{e\mu}$, $\epsilon_{e\tau}$, $\epsilon_{\mu\mu}$, $\epsilon_{\mu\tau}$ and $\epsilon_{\tau\tau}$ the relatively better discovery reach of CP violation is possible at their NSI values -1, ± 0.3 , 0.5, -0.6, -0.3 and 0.5 respectively for both the hierarchies over 84%(82%), 97%(97%), 98%(98%), 69%(75%), 75%(75%) and 86%(83%) respectively of the allowed δ values for normal (inverted) hierarchy .

In figure 5 we have shown at 5σ confidence level the discovery of NSIs ϵ_{ee} , $\epsilon_{e\mu}$ and $\epsilon_{e\tau}$ for baselines 3000 Km and 5000 Km baselines for neutrino factory and 2300 Km baseline for superbeam.

In figure 6 we have shown at 5σ confidence level the discovery of NSIs $\epsilon_{\mu\mu}$, $\epsilon_{\mu\tau}$ and $\epsilon_{\tau\tau}$ for baselines 3000 Km and 5000 Km baselines for neutrino factory and 2300 Km baseline for superbeam. In general the NSI discovery reach is better for 3000 Km baseline with neutrino factory for different NSIs except $\epsilon_{\mu\mu}$ (for which 5000 Km baseline in neutrino factory is better) and $\epsilon_{\mu\tau}$ (for which 2300 Km baseline in superbeam is better). In case of 3000 Km baseline for ϵ_{ee} the NSI discovery is possible for its value above about ± 0.1 except δ values around $225^\circ(225^\circ)$ and $80^\circ(50^\circ)$ for normal(inverted) hierarchy where the respective NSI values are slightly higher. For 3000 Km baseline for $\epsilon_{e\mu}$, $\epsilon_{e\tau}$, $\epsilon_{\mu\mu}$, $\epsilon_{\mu\tau}$ and $\epsilon_{\tau\tau}$ the discovery is possible below -0.02 and above 0.02 (below -0.02 and above 0.02), below -0.04 and above 0.02 (below -0.02 and above 0.05), below -0.18 and above 0.18 (below -0.18 and above 0.2), below -0.015 and above 0.015 (below -0.015 and above 0.015), below -0.18 and above 0.18 (below -0.18 and above 0.18) respectively for normal (inverted) hierarchy.

IV. CONCLUSION

We have made a comparative study of different baselines 2000, 3000, 4000 and 5000 Km baselines for neutrino factory and 130 Km and 2300 Km baselines for superbeam in studying discovery reach of CP violation, precision of measurement of δ for standard interactions. We have also made comparative study of baselines 3000, 5000 Km for neutrino factory with 130 Km for superbeam for CP violation discovery reach and with 2300 Km baseline for superbeam for NSI discovery limits. We have considered 130 Km baseline with super beam as it is found to give better discovery reach in comparison to other baselines for superbeam [15]. Similarly we have considered 2300 Km baseline with superbeam as it is found to give better NSI discovery limits in comparison to other baselines for superbeam [15]. In comparing baselines for neutrino factory with baselines for superbeam we have considered some conservative setups as mentioned in GLOBES. However, if the technology is further developed for superbeam [16] our conclusion could differ.

Considering standard model interactions only we find that for CP violation discovery reach 3000 Km baseline for neutrino factory is somewhat better than other baselines with neutrino factory or with superbeam as found in figure 1. However, for precision of measurement of different values of δ (true) both 3000 and 4000 Km baselines for neutrino factory seem to be good as seen in figure 2. In presence of non-standard interactions $\epsilon_{e\mu}$ over the entire allowed range and $\epsilon_{e\tau}$ for most of the allowed region 3000 Km baseline for neutrino factory is found to be good for CP violation discovery reach. The possible reason for this feature has been discussed in section II from the expression of $\nu_e \rightarrow \nu_\mu$ oscillation probability. One advantage of neutrino factory also lies in the detector for identification of muon instead of electron which is required in superbeam. We find that the NSI discovery reach is better for 3000 Km baseline with neutrino factory for different NSIs except $\epsilon_{\mu\mu}$ and $\epsilon_{\mu\tau}$. So it seems that if we consider CP violation discovery reach, precision of measurement of δ as well NSI discoveries 3000 Km baseline in neutrino factory performs better in most of the cases for various allowed range of NSI parameters.

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